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MANUAL FOR  
FLUXGATE FERRITE MAGNETOMETER

## FERRITE FLUXGATE MANUAL

### Purpose

The purpose for the construction of four single component magnetometers complete with electronics was that the various groups within NASA concerned with space magnetometry may be able to examine and test this new ferrite head. Accessibility, therefore, to the electronic components is desirable. Unfortunately, accessibility is not entirely compatible with compactness or potting. To facilitate probing of the circuits, components of necessity had to be laid out rather than built up in cordwood sets in permalloy shield cans. For the same reason transistors were mounted somewhat unconventionally for ease in circuit tracing. They were also soldered in place rather than plugged into the usual sockets to avoid an unnecessary possible source of instrument drift. Thus it is clear these models are not intended to exhibit the ultimate achievable packing density or lightness.

### Advantages and Limitations of Fluxgate Magnetometers

The ferrite tubular fluxgate magnetometer sensor is essentially an ambient magnetic field chopper, sensitive to the surrounding field component parallel to its axis. It therefore partakes of the well known advantages of chopper amplifiers as well as properties peculiar to ferromagnetic materials and the geometry of the sensor.

The tubular sensor represents an effort to decrease core losses by reducing core volume. Earlier efforts produced the permalloy tube<sup>1</sup> with a

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<sup>1</sup>

Air-Borne Magnetometers for Search and Survey, AIEE Transactions, 47, v. 66, p. 641 ff

slight overlap like the paper shell of a cigarette, thus maintaining desirable length and consequent sensitivity. Toroidal winding of the drive coil on the tube was then developed to decouple the drive winding from the output by orienting the driving or saturating field perpendicular to the axial field to be detected. Later the tube was fabricated from a series of interwoven helices having a braided appearance.<sup>2</sup>

Professor Thomas Gold of Cornell suggested that ferrites might provide unique properties useful in magnetometry. The braided tube is an attempt to maintain high axial effective permeability and a more stable circumferential path for the cyclically saturating drive flux. It is necessary of course to insulate the permalloy strips from each other to prevent the formation of a shorted turn on the axis of the pickup or secondary winding.

Ferrites on the other hand are insulators. Thus braiding of insulated fragile permalloy foil is unnecessary; tubes can be machined directly. Furthermore the braided configuration constrains the drive field to zig-zag longitudinally along the same path as the field to be detected. The solid ferrite core does not impose this defeat of local orthogonality on the sensor and thus makes possible inherently better isolation of the secondary from the drive signal and its distortion components.

Perfect orthogonality is never reached, nor is a perfect drive signal achieved. Thus, even harmonics of the drive signal inevitably cause a net axial perm which is then detected as though it were a bona fide ambient field. A well wound sensor will typically indicate 40% offset for one

percent second harmonic even in such a phase that the coupled through signal is rejected by the synchronous detector. The effect continues for all even order harmonics in the drive system because added to the fundamental the resultant is negative and positive peaks of differing value, hence the net perm introduced circumferentially and, unfortunately, axially as well.

It is then clear that the drive waveform must be sufficiently free of even order harmonics to reduce the drift cause by them below the irreducible Barkhausen drift or low frequency axial core noise components if a sensor is to be best utilized. Certainly second harmonic contamination of the drive system must be below 0.01% if drift below 0.4γ is to be possible.

The natural inclination would be to devise a push-pull oscillator coupled to a low distortion amplifier and then pass the signal through enough filtering to meet the specifications. A filter capable of delivering the necessary power to a ferrite sensor is altogether too bulky and heavy for flight. Besides, the usual output of such a filter, a sine wave, is not the optimum drive waveform but rather a waveform containing odd harmonics in certain proportions.

In order to supply the peak current necessary to deeply saturate the core and to give reasonable output per gamma of ambient field a capacitor is connected across the drive winding. During the non-saturated period of each half cycle we have in effect a low frequency tank circuit. During the saturated period we have a high frequency tank. In the transition periods the instantaneous resonant frequency changes smoothly from the one extreme to the other. Any LC circuit used as part of a filter and having

a permeable core inductor will have the same effect for large signals and generate odd order harmonics. Shock excitation of our sensor primary tank shows on a scope a damped oscillation somewhat like a square wave that varies in 'average' frequency roughly inversely with the depth of saturation.

Thus we see the oscillator frequency must track the average resonant frequency of the tank which itself is affected by the drive level and incidentally by the sensor core temperature. And both should be controlled to remain within the bandpass and phase shift limits of the second harmonic signal filter and demodulator.

If the tank peak current is held constant by a drive regulating circuit the natural tank frequency will be held well within sufficiently close limits for the filter. It then is possible to use the tank waveform itself to drive the oscillator.

The remaining problem is to make a signal source with what must in effect be a comb filter suppressing all even order harmonics. In the accompanying equivalent circuit for the drive circuit Sw-1 and Sw-2 are transistor switches corresponding to  $V_1$ ,  $V_3$ , and  $V_2$ ,  $V_4$  on the main schematic. The DO-T14 UTC transformer acts as a shunt source for collector DC voltage.  $R_c$  is the very high collector impedance of grounded base transistor  $V_5$ . If the transformer has no significant residual perm of its own to contaminate our system and is accurately center tapped and if the switches open and close alternately at the crossover time of the sensor tank we will make up the tank losses at a very constant rate throughout each cycle, thus giving us a waveform low in even harmonics.

Consider a possible source of unbalance, variation in switch resistance or transistor saturation resistance. If the resistance of the two switches were to mistrack by as much as 0.5 ohm this would be of no consequence since it is in series with  $R_c$  which is of the order of megohms. Thus the rate of make-up of tank losses on each half cycle is determined essentially by  $R_c$  which can easily be kept constant from cycle to cycle with high precision. Further, the transformer used as a center tapped reactor can be much smaller than if used in its usual transformer mode. And if the operation of the switches is governed by the tank crossover points and not by the feedback time constant we have a tank loss make up system that is exceptionally low in even order harmonics without power filter components and in spite of mismatching and mis-tracking push pull transistors.

The remaining possible circuit causes for even harmonic distortion are asymmetrical transformer arms, rapid changes in  $R_c$ , and the half cycle loading of each of the transistor switch base drive arms feeding  $V_3$  and  $V_4$ .

Transformer arm asymmetry is low but constant and may if desired be compensated in the demodulator balancing circuit. Rapid changes in  $R_c$  due to signal or noise leakage into  $V_6$  is held to adequately low levels by the 4.5 hy choke and 200 $\mu$  f filter at the base of  $V_6$ . Half cycle loading of the sensor drive by the transistor switch base circuits is greatly reduced by the use of Darlington pairs so that trimming of the 10K or 100K resistors has slight effect on balance and is a vernier adjustment that may be used when a sensor is tested by repeated turnover in a zero field facility. By this means slight offset caused by the transformer may be

nulled, the demodulator being left optimally balanced.

As the temperature of the sensor core changes, core losses change and the drive circuit must automatically compensate. An ordinary critically balanced push pull drive circuit will have to shift its operating point to compensate, thereby departing from its balanced state. Our present circuit allows change in operating area of the transistor switches without significant change in output purity because of the very long 'tail',  $R_C$ . Overdrive systems used to deperm sensors have previously suffered from this heretofore inescapable unbalance during ringdown with resultant perm, which in turn will drift unpredictably toward but never reach zero. Our present system deperms more reliably and is arranged to deperm the sensor each time the power source for the magnetometer is turned on. Further, frequency stability is entirely adequate for the signal filter over a better than 20-25v DC supply range. In case the supply voltage falls below approximately 17v power demand drops sharply to less than 1/4 normal, lessening the likelihood of complete discharge of a battery set if used.

Drive frequency is determined by the sensor primary shunt capacitor, the volt-time integral necessary to saturate the sensor core, and this in turn by core volume, number of primary turns, and the DC current through  $R_C$ . The frequency of 5 KC was chosen to be high enough to be above flicker noise and the second harmonic in the range where easily available components could be used.



A ringdown tapered from high slowly to operating level has been found to be even more effective when done with the sensor secondary shorted, possibly by constraining the 'sticky' domains to align perpendicular to the sensor axis.<sup>3</sup> The overdrive system now in use also raises the drive frequency placing the second harmonic quite above the sensor secondary tank resonant frequency. Thus the secondary 'sees' a low impedance load during primary ringdown and deperming effectiveness is enhanced. Those domains on the threshold of turning at operating level and which only occasionally respond to the drive contribute drift. Shorted secondary ringdown seems to reduce their activity and the consequent drift for several minutes.<sup>4</sup>

#### Parametric Amplification in the Tubular Toroidally Wound Sensor

The cyclically saturated sensor core causes the secondary winding inductances to vary correspondingly with the result that in conjunction with its resonating capacitor parametric amplification occurs at the second harmonic or signal frequency. Thus the drive level must be kept below the level at which the secondary will oscillate or alternatively the secondary must be suitably loaded. The loading can be done with a step up transformer to most fully utilize the amplification. It was found, however, that available miniature transformer's core losses necessitated an uneconomically

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<sup>3</sup> Final Test Report to NASA, Contract NASr-46, CRSR 141.

<sup>4</sup> Ibid.

high drive level. Instead an extra layer of sensor secondary winding was employed as an impedance transformer.

To determine how far this effect could be carried an audio power amplifier was used as a temporary driving source and a sensor secondary loading resistor chosen to stabilize the sensor below self oscillation. At approximately ten watts (intermittently applied) drive a forty volt peak output was observed and photographed for a 40V peak of ambient AC magnetic field hum. A compromise therefore had to be established between power economy and the need for post sensor signal amplification. At the present the entire electronics package requires 0.56 to 0.8 watts, depending mainly from unit to unit on the sensor's core losses.

Thus we have a drive system that is inherently low in even order harmonics over a wide range of driving levels, that is adequately frequency stable, that automatically deperms the sensor each time there is a power interruption of more than several seconds, that has no undesirable starting transients, and approximates a shorted secondary during starting ringdown for most effective deperming. If the magnetometer is to be used intermittently then the temporarily lower Barkhausen axial core noise following shorted secondary ringdown will be attractive. And further, the drive system is easily adapted to drive all three sensors of a three component system simultaneously with better economy than three separate oscillators.

There was insufficient time to test a full spectrum of ferrite sensors for magnetic annealing which holds promise of even lower axial Barkhausen noise and consequent drift.

### Demodulation

Considering the various types of single ended and push pull diode and transistor demodulators and their characteristic offsets it was determined that the diode ring offered the most stable performance.<sup>5</sup> A reference square wave is to be preferred to a sine wave and symmetry about both zero voltage and time axes is necessary. The present drive circuit does not supply even an approximation to a sine wave at the second harmonic but does by means of the sensor primary tank current sampling resistor, step up transformer, and full wave rectifier provide positive spikes at 10 KC that track the saturation times and therefore second harmonic signal phase of the sensor as its temperature is varied from 20°K below its Curie point (423°K) to below 230°K. The bottom limit has not been determined.

Schmitt triggers require good sine wave triggering to yield symmetrical square waves. Synchronizing a free running multi-vibrator and triggering a monostable MV are the two remaining options. The present circuit uses the monostable MV which is adjustable for time symmetry. The required stability of trigger frequency for square wave time symmetry is supplied by the drive system already described.

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Design Criteria for the Semiconductor Ring, E. Channel, Electrical Design News, 1/64, p. 76ff

### Signal Amplifier

Low noise, stable adequate gain to facilitate an overall negative feedback loop from the smoothed demodulator output to the sensor core, simple circuit, and a floating output are the requirements. These are adequately met using complementary transistors.

### 10 KC Signal Filter

Flat bandpass over the expected frequency range, nulls at the drive frequency and third harmonic, as well as low insertion losses at 10 KC are the requirements. The idea of an active filter was entertained but development was prevented by lack of time.

### 10 KC Signal Preamplifier

Low noise impedance transformation to match the high sensor secondary impedance to the low impedance of the filter network are the basic requirements. It would be desirable in addition that the preamp should not be harmed by sudden large transients from the sensor nor should it pass them on to the filter and subsequent amplifier without compression. Since the sensor will normally be operating with negative magnetic feedback its output level will be no more than a few millivolts. Signals higher than 50 mv are compressed without additional components and without component damage until the negative feedback restores the core to near zero field.

The preamplifier is sensitive to coupling of signals from other circuits through the common power supply. Decoupling of the stages progressively from the power source and from each other is done with series diodes and filter capacitors rather than resistors and capacitors. The diodes waste less power and decoupling is much improved for given capacitors.

#### Negative Magnetic Feedback

A 'DC' current varying in polarity and strength with the magnetometer output is applied to the sensor secondary so that the secondary generates a magnetic field in the sensor in reverse polarity to the ambient field. Thus linearity of output with respect to the ambient field component parallel to the sensor axis is improved and calibration is stabilized. Current injection into the sensor secondary (or any separate secondary winding) via a resistor would load the sensor output tank reducing its Q and sensitivity. A guarding circuit in conjunction with the preamplifier is used to obviate the difficulty. Final balance adjustment for zero field indication requires a zero field facility and accurate turn-over provision (Page 5).

#### Areas for Possible Future Investigation

The ferrite sensor cores are now as small as they can be made and still not break up during machining and winding. One could imagine if they were strong enough making the wall thickness so little their porosity would become a limiting factor in maintaining

the necessary low percentage variation in wall thickness. This limit might be approached and the core losses still further reduced by forming the 'green' ferrite on a tubular ceramic mandril before firing. After curing, the ferrite, being fully supported by the ceramic substrate, could be machined to a much lower wall thickness. The ceramic base would supply the strength not only for machining but also for the later winding.

General Ceramics T-1 material was used. Their new 0-5 samples arrived too late for machining. It is finding use in TV flyback transformers and should be as much an improvement for our purposes as theirs provided the noise level is correspondingly better.

Hard potting materials around T-1 sensors absorb magnetostrictive energy and so raise core losses by  $1/3$  to  $1/2$ . Close fitting the sensor in a soft paper sleeve within a glass tube for full length suppose seems to safeguard the ferrite tube as long as the glass tube remains intact. Potting, if used, should be of a foam type to minimize magnetostriction energy absorption.

Magnetic annealing would seem to be an excellent means for aligning sticky domains permanently perpendicular to the sensor's axis, thus removing a significant portion of the Barkhausen noise (drift) from being coupled into the sensor secondary. There was insufficient time to test a full series of ferrites for this property.

Sync signal pickoff from the drive circuit is a likely source for second harmonic contamination and was minimized by use of a Darlington circuit. A guarded Darlington or even better a field effect transistor should provide closer to optimum performance. Best of all would be the FET fed from the top of the 'long tail'.

The preamp would also profit from the low noise characteristic of FET's.

#### Additional References

Ferrites, J. Smit and H. P. J. Wijn, p. 60 ff, 1959, John Wiley and Sons, Inc.

Development of Single-Component Magnetometer, Heli Flux<sup>R</sup> Sensor Type Model CRC-IX, Final Report, Air Force Cambridge Research Laboratories No. 1099

Quarterly Status Report to the National Aeronautics and Space Administration, Space Magnetometer Development, NASA Contract NASr-46, March 1, 1963 to June 1, 1963, CRSR No. 124

Demagnetizing Factors of Rods, R. M. Bozorth and D. M. Chapin, Journal of Applied Physics, 5/42, v. 13, p. 320 ff.

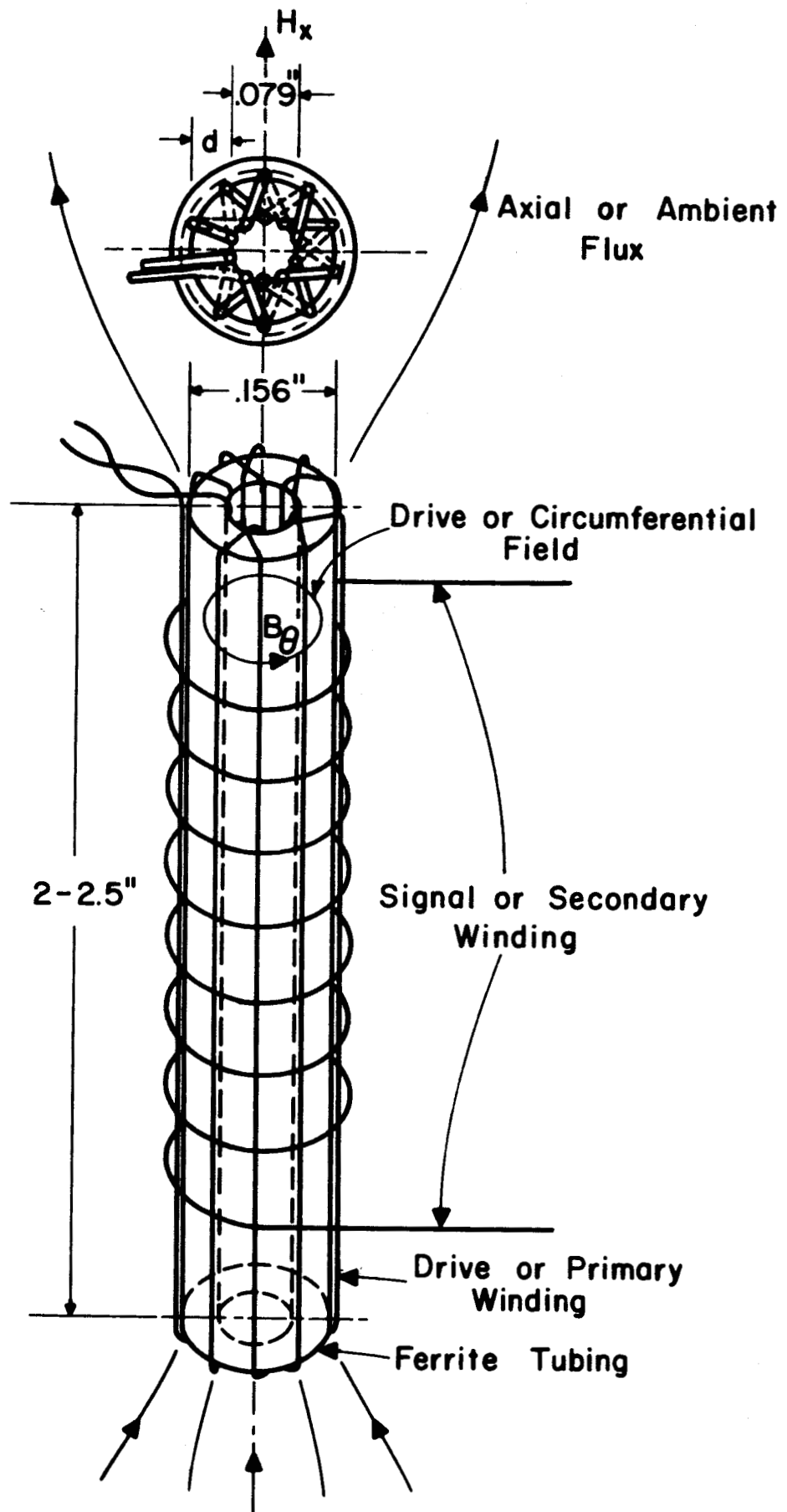
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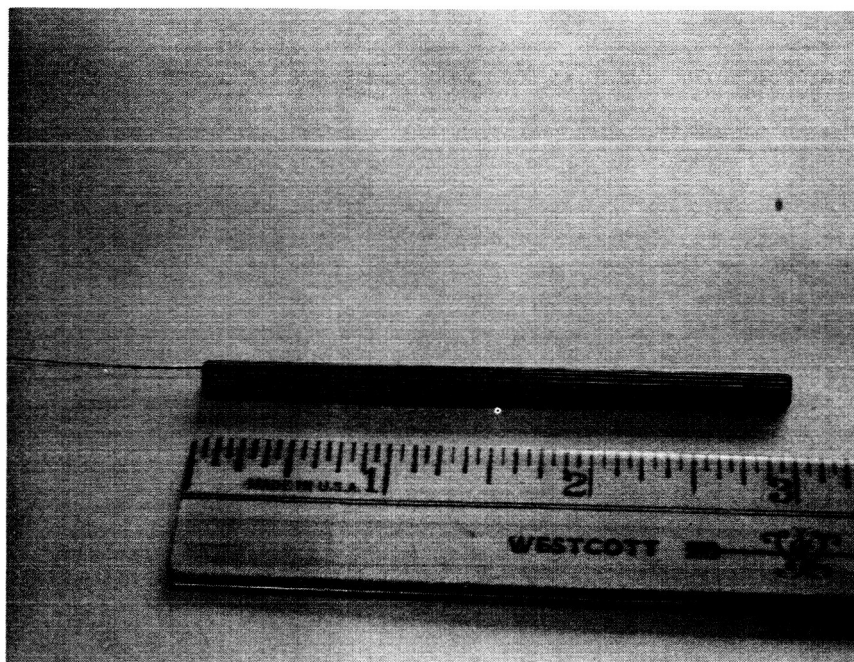
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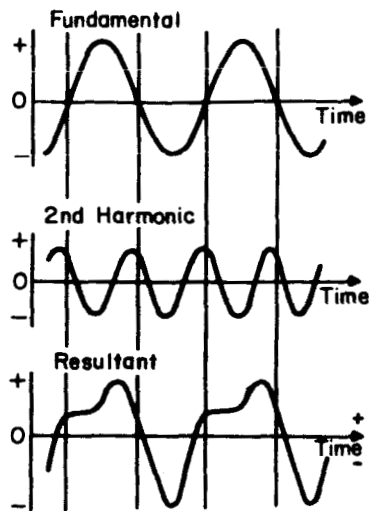
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Sensor Ferrite core with  
drive winding in place



In the sensor drive winding an even harmonic added to the fundamental causes a net perm because the resultant negative and positive peaks saturate the core unequally.

Equivalent constant current switching model of sensor drive circuit.

